CHAPTER 2

COIL DESIGN

2.1 General Features

A cross section of the DØ detector together with the solenoid is shown in Figure 2.1 with flux lines and field values superimposed on it from a 2D calculation of the solenoidal field. From the values of the field shown in Figure 2.1 it is seen that the field of the solenoid rapidly falls beyond the end of the magnet. In order to maximize the field uniformity inside the bore of the solenoid over as large a volume as practical the current density in the windings is made larger at the ends of the coil. This leads to the use of two grades of conductors with different thicknesses. Both grades of conductors are made with a superconducting Rutherford cable of multifilamentary Cu-NbTi strands stabilized with pure aluminum. For specificity, the basic strand chosen is of the SSC-type with Cu:NbTi ratio 1.3:1 and diameter 0.808 mm.

The solenoid is wound with two layers of aluminum stabilized superconductor to achieve the required linear current density for a 2 Tesla central field, as shown schematically in Figure 2.2. The support cylinder is located on the outside of the winding to support the radial Lorentz forces on the conductor.

The use of pure aluminum in the conductor yields a low resistivity stabilizer for the superconductor while reducing the interactions of particles in the material of the conductor. Aluminum is chosen for the support cylinder and vacuum vessel of the magnet cryostat also to achieve low particle interaction rates in the balance of the magnet structure.

The coil is indirectly cooled by two-phase liquid helium flowing through an aluminum cooling tube which is welded to the outside surface of the support cylinder. For stability the coil relies on the specific heat and high thermal conductivity of the high purity aluminum stabilizer and by a conservative margin of the critical current of the superconductor beyond the operating current of the magnet. The presence of the support cylinder ensures quench safety by the rapid spreading of the normal zone in the event of a quench (the "quench-back" effect) [1], a typical feature of magnets of this type.

2.2 Conductor Selection

For practical reasons the maximum operating current of the magnet is set at 5000 A and the size of the conductor and the superconducting insert is chosen accordingly. Considerations of available technology for the coextrusion of pure aluminum and the margins of stability desired for such a magnet led to a choice of overall conductor cross-section and a two-layer winding design. By adjusting the conductor final size accordingly two grades of conductors improve the field homogeneity.

The cross sections of the two grades of aluminum stabilized conductor are shown in Figure 2.3. Both grades use the same superconducting insert and only the amount of aluminum stabilizer is varied between them. The larger conductor is 5.125 mm wide and the smaller conductor is 3.820 mm wide. Both conductors have a radial height of 15 mm for simplicity of forming joints between the two grades and overall ease of winding. The cable within the conductor is placed at a location in the cross-section that is most appropriate for the coextrusion process and the subsequent bending of the finished conductor as the coil is wound. The superconductor is shown placed nearest the inside radius of the conductor in Figure 2.3. This choice of location maximizes the region of pure aluminum that can be used for the making of welded joints between conductor lengths during coil winding. The finished overall dimensions of the conductor are readily held to tight tolerances to ensure uniform coil winding. The final shape of the conductor may be keystoned slightly if necessary to accommodate any distortion due to the rather high prestrain caused by conductor winding.

There are several considerations to be addressed when making a choice between monolithic and cabled superconductors. Earlier thin solenoids such as **CDF** [2] were made with monolithic superconductors. More recent solenoids (**ALEPH** [3], **ZEUS** [4], **CLEO II** [5], and the **SDC** model [6]) were made with cabled superconductors. A cabled superconductor is preferred for the following reasons:

1. Longer lengths of finished conductor are more easily made. With a cabled superconductor, original billet size does not limit the length of finished conductor that can be made. Occasional strand joints are permissible and the overall risk of the conductor production is lessened.

2. The technique of coextruding high purity aluminum with a cabled superconductor is well established in industry. Adequate capability has been demonstrated for producing finished conductor of the required length having high quality intermetallic bonding, while preserving excellent low resistivity in the aluminum and maintaining tight control over finished conductor shape tolerances.

3. Many industrial suppliers have produced high quality stranded cabled conductor for recent accelerator projects including **HERA**, **RHIC**, and the **SSC**, as well as for other commercial applications. Thus suitable cabled conductor is readily available and may cost less than a custom made monolithic conductor. Because the cable strand design is not greatly restricted by the final design of the finished conductor the delivery time of the finished conductor can be lessened as well.

4. With a bending radius of about 0.58 meters as required by the size of the solenoid, a superconducting cable insert should permit adequate formability of the conductor

section must be chosen with this coil winding requirement in mind.

The desired superconductor critical performance is shown in Figure 2.4. The load line of the magnet and the operating line for the peak field on the conductor is shown. The peak field on the conductor is 2.2 T when the magnet central field is 2.0 T, as shown in Figure 2.4. The peak field occurs in the inner layer winding at the point where the current density increases near the end of the coil. The critical curves for the superconductor are generated by scaling from SSC-type cable performance. At 2 Tesla, the typical current carrying capacity of the SSC 30 strand cable is 34500 A at 4.2 K [7]. This leads to 18400 A for the 16 strand cable at 4.2 K. At an operating temperature of 5.1 K, this cable would have a critical current of about 14460 amperes; the magnet operates at 55% of this current (along the load line) at design field.

2.3 Winding Design

The two grades of conductor are used in both layers. The middle section of each layer is wound with the wider conductor and the end sections with the narrower conductor. The transition point between the two grades of conductor in the inner layer occurs at z= ± 0.953 meters from the center, while for the outer layer this transition occurs at z= ± 0.653 meters from the center. With this straight-forward grading of the current density it is possible to achieve a sufficiently uniform field inside the solenoid volume as will be described in Chapter 3. In order to reduce the maximum field on the conductor the outer layer transition point occurs at a smaller z than the transition in the inner layer. A summary of the calculational parameters of the solenoid is shown in Table 2.1. Note the current blocks correspond to the radial locations of the superconducting inserts in the conductors, with the current smeared uniformly in z. The field calculations resulting from this winding design are described in Chapter 3.

2.4 Conductor Joints

There are four places in the solenoid where the conductor width changes, two on the outer layer and two on the inner layer. At these locations the two grades of conductors are joined with a lap joint and edge-welded as indicated in Figure 2.2. The welding of a 40 cm length is done at four places along the one overlapping turn of both grades of conductors. This will make an estimated resistivity of 4×10^{-10} Ohm at 4.2 K at each joint [2]. This type of joint entails the effective loss of one turn per transition point. This loss has been incorporated in the field calculations described in Chapter 3. It is desireable that there be no other joints in the coil.

Winding Procedure

The conductor is located inside the support cylinder which counteracts the outward Lorentz forces on the conductor and provides axial rigidity to the finished coil. At both ends of the winding the conductor is compressed axially toward the center of the winding by the fringing field. During operation the solenoid should not quench or exhibit undesireable training or other instabilities. This implies that the winding structure must be tight and rigid so that it is everywhere free from inelastic conductor motion that can cause quenching. In particular it must be bonded securely and permanently to the support cylinder so that the axial stresses do not cause debonding between the coil and the cylinder. In addition to being a source of quenching this debonding would jeopardize the heat transfer between the coil and the cylinder that is critical to the performance of the magnet.

In practice understanding the winding preload and the integrity of the epoxy used to bond the turns to one another and to the support cylinder ensures that the coil will perform as intended. The radial and axial winding preloads must not exceed the effective yield strength of the pure aluminum in the conductor but they must be sufficient to fully "bed down" the winding structure during fabrication so that the effective compressive modulus is truly as high as that used in the finite element modeling of the windings.

The epoxy or other impregnant selected for the winding, and any other electrical insulation material used, must tolerate the specified mechanical stresses at low temperatures and should not exhibit cracking or other degradation. The fabrication procedure must be devised to achieve the desired preloads so that a coil structure of high mechanical and thermal integrity is obtained.

It is almost certain that because of the small radius of the coil the conductor must be wound on a temporary mandrel and the support cylinder installed over it [4], rather than wound directly inside the support cylinder as has been done with larger solenoid magnets [3]. It may be necessary to "pre-bend" the conductor as it leaves the storage spool and goes onto the winding mandrel.

Two general approaches have been taken for the binding together of the windings of thin solenoids: winding with b-staged turn-to-turn insulation [2, 8] or winding with dry insulation followed by a vacuum impregnation with epoxy [4].

A variety of techniques have been used to provide the coil with a tight-fitting outer support cylinder. The coil can be cured, machined to a precise outer diameter, and a shrink fitting procedure used to install the outer support cylinder [2, 4]. Alternatively, the coil is cured in the outer support cylinder in which it was wound [3, 8], or cured in an outer support cylinder installed after winding [9].

A number of considerations must be addressed to develop the winding procedure:

1. Winding and assembly of the solenoid must be done in an isolated and clean area to ensure that no foreign conductive chips nor irregularities on the conductor, winding

[illegible] the coil.

2. If winding on the inside of the support cylinder is not feasible, a temporary collapsible but rigid winding mandrel can be made which has an accurate and smooth outer diameter machined to a tolerance of at least $\pm$ 0.05 mm.

3. A layer of fiberglass-epoxy insulation several millimeters thick is built up on the mandrel, using b-staged sheets or the like, compressed to high glass fraction and cured as specified. Considerations of debonding the mandrel from this layer after the coil is finished must be addressed when this insulation layer is designed.

4. The insulated surface of the mandrel is then machined to an accurate and smooth diameter to a tolerance of at least $\pm$ 0.05 mm. The final thickness of the insulation is arbitrary, but it needn't exceed a millimeter or so. The final dimeter of the insulated mandrel is chosen to be that required by the coil design.

5. End flanges to support coil winding and axial preloading are then attached to the winding mandrel. Depending on subsequent fabrication steps, these flanges may require later replacement. The final shape and geometry of the winding surface is documented by careful measurement.

6. After providing for the doubling of the input bus to the magnet coil, winding then proceeds. The input bus can be made of two standard conductors edge-welded for 10 cm. long every 30 cm. The details of conductor final inspection and insulation, winding pretension, temporary axial clamping, etc., take place as required by the final winding design choices. Provisions for making joints between conductor grades is made when transitions between current densities is required, as is constant monitoring for shorts to ground and turn-to-turn, as well as documenting the geometry of the windings and joint locations as the layer proceeds. When the first layer is completed, the winding transition to the second layer is provided.

7. Layer-to-layer insulation is installed, and if a b-staged (or wet layup) winding design is used, it may be necessary to clamp and cure the first layer at this time. The second layer is wound much like the first, with the same attention to winding detail as outlined in step 6 above.

8. When the final turns are installed, the outlet bus is reinforced like the inlet bus as described in step 6. As with the inlet bus, extra length is left attached and appropriately stored so that the magnet buswork in the service chimney can be later installed without unnecessary joints.

winding design was used this might be more b-stage sheets overwrapped and the coil clamped and cured. If an impregnated winding design is chosen this might be bare glass cloth, after which the coil is clamped, enclosed, and then vacuum impregnated and cured. The outer surface of the coil is machined to a precision of at least $\pm$ 0.05 mm, leaving a total outer insulation thickness of about 2 mm. The final diameter is accurately measured and the coil is tested for shorts to ground.

10. The outer support cylinder is machined to an interference ID to the coil. Before final machining the helium cooling tubes and support attachments can be welded onto the OD of the support cylinder.

11. The machined support cylinder is heated to a temperature rise of 100° Celsius. The cylinder will expand approximately 3.1 mm on the diameter so that the final room temperature interference can be chosen with regard to the clearance needed for the heated insertion procedure. The cylinder is then lowered over the coil which is standing vertically on its axis, and allowed to cool. The coil may be lubricated with a suitable epoxy prior to installation of the support cylinder.

12. Depending on the winding design details the end flanges of the support cylinder are attached to it and preloaded if necessary unless they are already in place. The collapsible winding mandrel is removed and final measurements and tests are then made on the completed winding.

13. The coil temperature sensors and potential taps are installed and the current buses routed and clamped as necessary.

References

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Parameter	Value
Current Region I	
Z beginning	0.0 mm
Z end	653.0 mm
R beginning	604.6 mm
R end	609.6 mm
Height of SC insert	5 mm
Total width of turn	5.625 mm
Number of turns	115
Total Amp Turns	554875
Area	3234.38 mm^2
Average Current Density	1.72 A/m^2
Current Region II	
Z beginning	0.0 mm
Z end	953.0 mm
R beginning	588.6 mm
R end	593.6 mm
Height of SC insert	5 mm
Total width of turn	5.625 mm
Number of turns	168
Total Amp Turns	810600
Area	4725 mm^2
Average Current Density	1.72 A/m^2
Conductor Current = 4825 A, $B_o = 2$ T	

Parameter	Value
Current Region III	
Z beginning	653.0 mm
Z end	1282.5 mm
R beginning	604.6 mm
R end	609.6 mm
Height of SC insert	5 mm
Total width of turn	4.32 mm
Number of turns	146
Total Amp Turns	704450
Area	3153.6 mm^2
Average Current Density	2.23 A/m^2
Current Region IV	
Z beginning	953.0 mm
Z end	1282.5 mm
R beginning	588.6 mm
R end	593.6 mm
Height of SC insert	5 mm
Total width of turn	4.32 mm
Number of turns	76
Total Amp Turns	366700
Area	1641.6 mm^2
Average Current Density	2.23 A/m^2
Conductor Current = 4825 A, B_o = 2 T	

B-Field Map for D0 Superconducting Solenoid

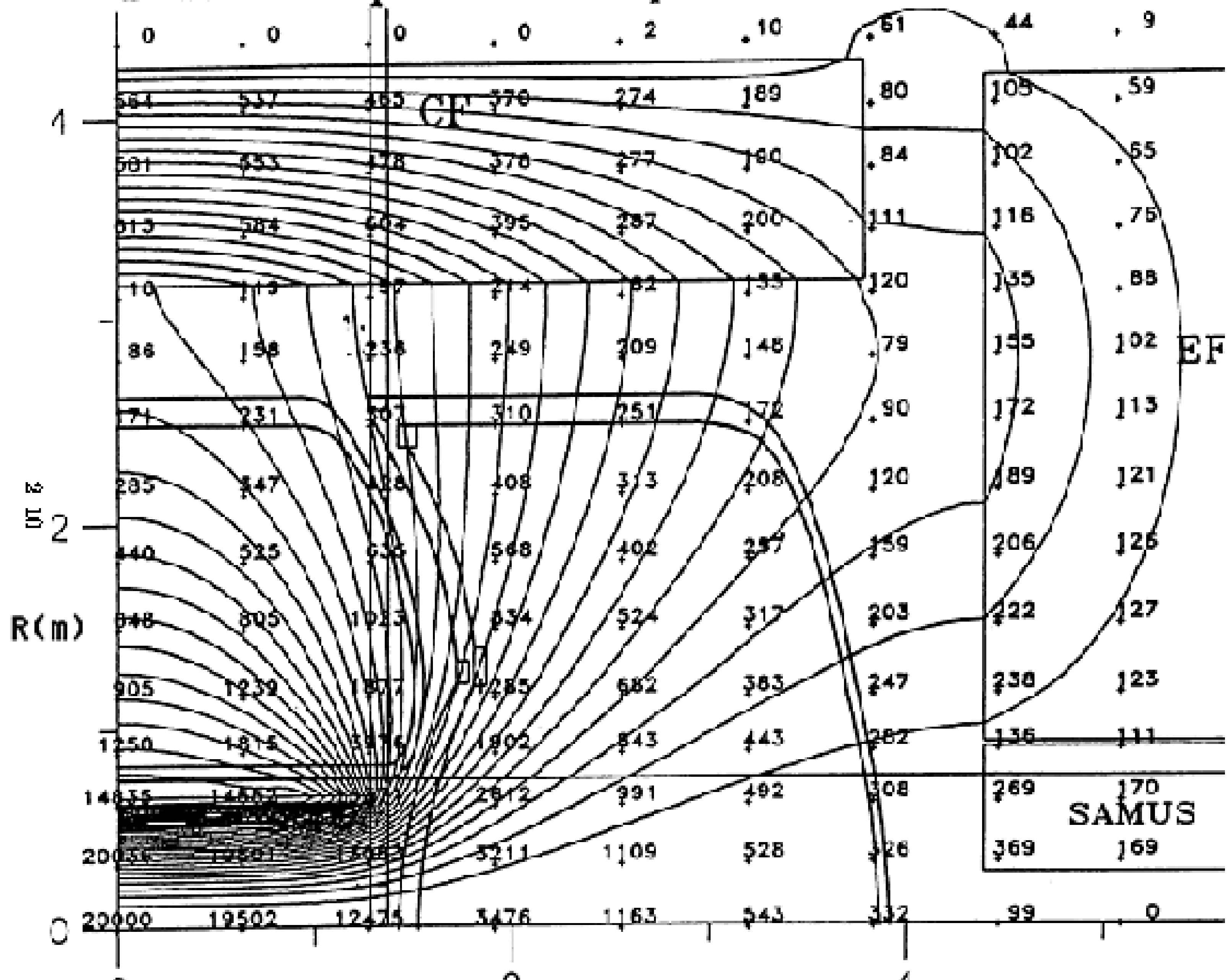

FIGURE 2.1

ILLUSTRATIVE COIL ASSEMBLY

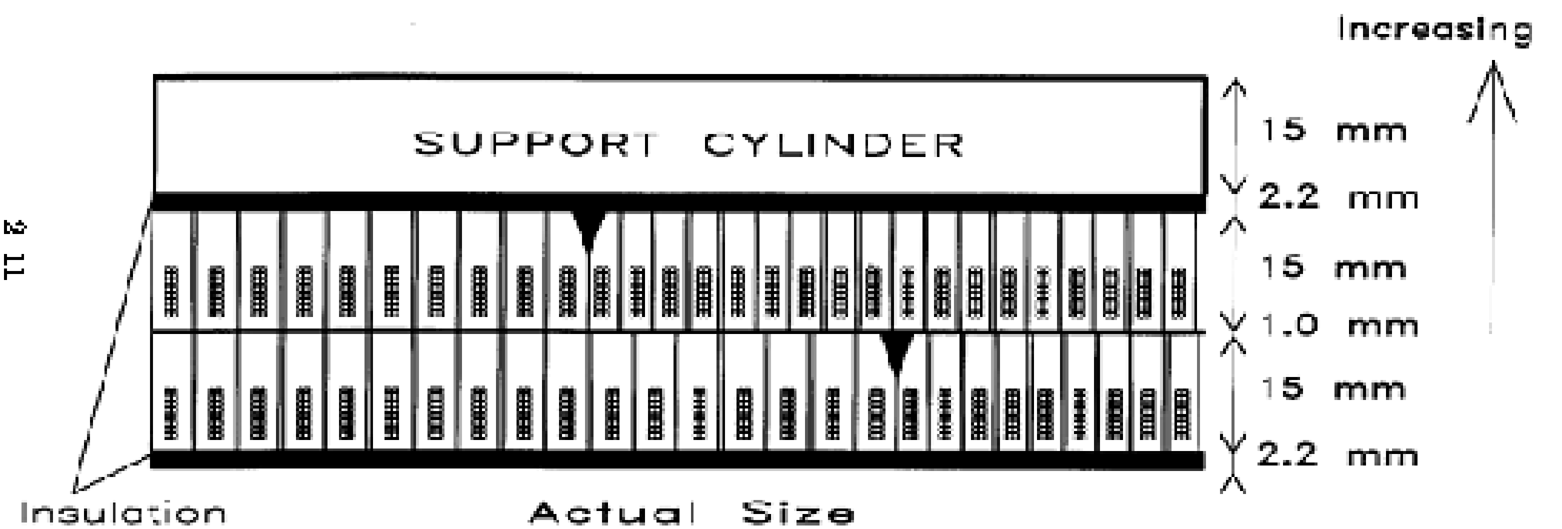

Figure 2.2

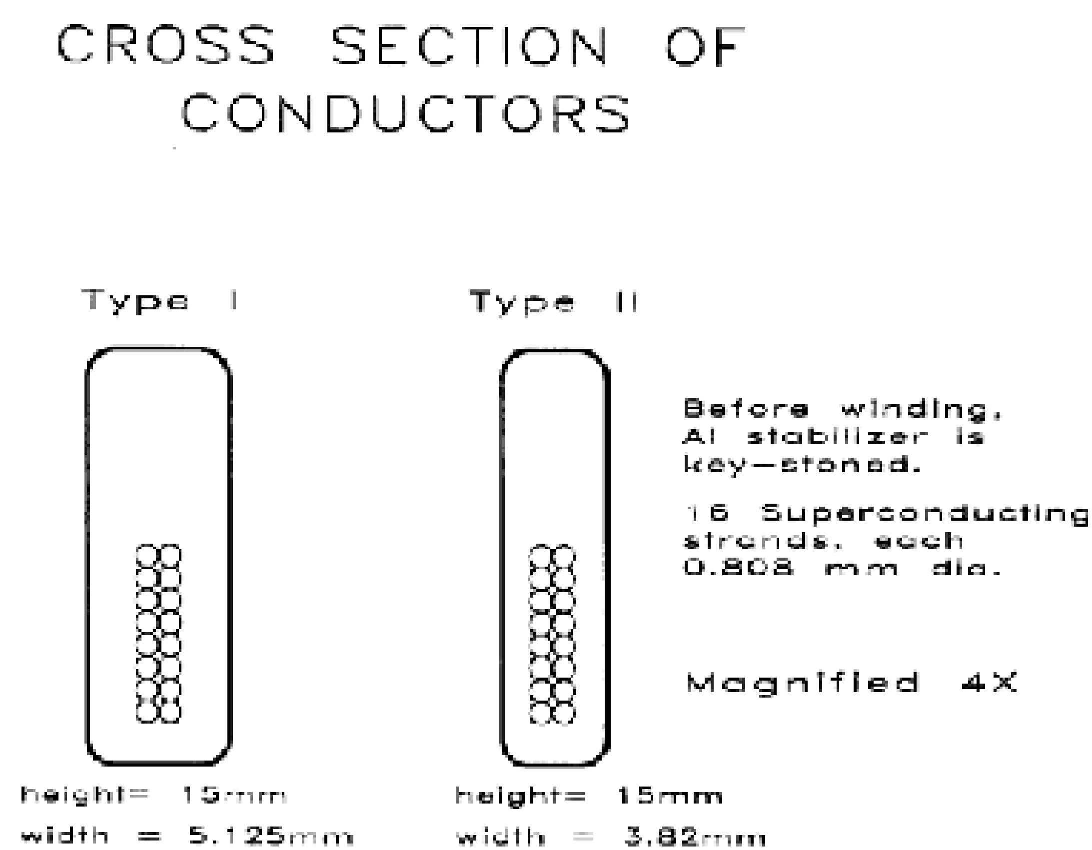
CROSS SECTION OF
CONDUCTORS
Type I
Type II
Before winding,
Al stabilizer is
key—stoned.
16 Superconducting
strands, each
0.808 mm dia.
Magnified 4X
height= 15mm
width = 5.125mm
height= 15mm
width = 3.82mm

Figure 2.3

SHORT SAMPLE DATA

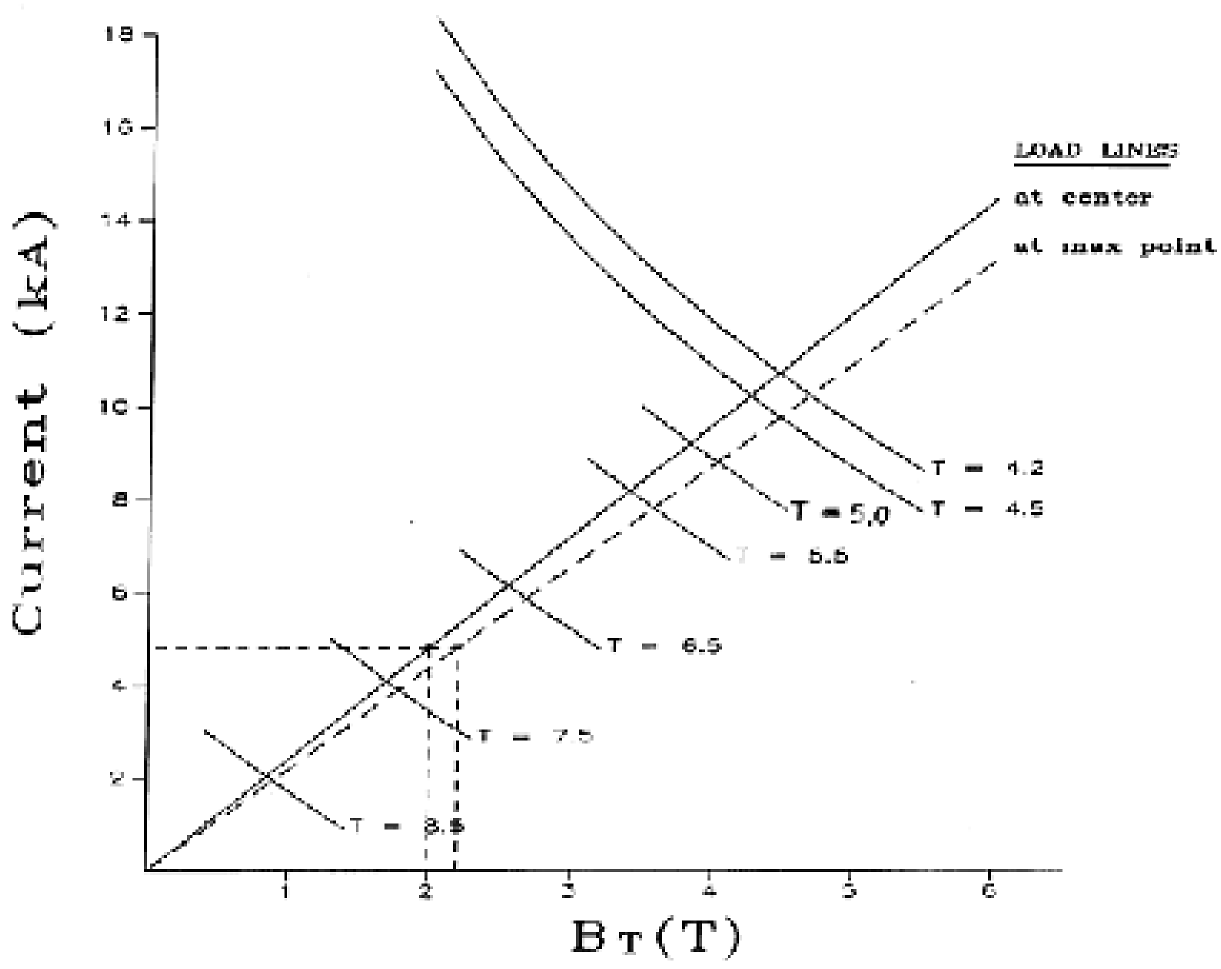

Figure 2.4